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Review

Climate change and its implications for developing brains – In utero to youth: A scoping review

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ABSTRACT

The brain health and development implications of climate change are situated within a large and rapidly increasing body of evidence that addresses the physical and mental health impacts and implications of extreme and worsening environments. The costs to individuals and societies of negatively impacted brain development are profound – be it in the form of diagnosable developmental disability, reduced cognitive capacity, or areas of behavioral functioning. We have sought to describe the key risk domains that climate change presents with respect to healthy brain development, from the prenatal through to youth stages. Scoping review methods and an a priori search strategy were used to address the question: What are the major considerations of the peer-reviewed literature that address climate change as it relates to brain development and health from early development through to youth populations? Themes from the identified papers were charted, and findings were summarized through a consensus process. A total of 40 papers were identified in the search, spanning 2008–2022. Based on the thematic analysis, results are organized into the following nine themes: 1) heat extremes, 2) weather extremes and stress, 3) air pollution, 4) vector and waterborne illnesses, 5) malnutrition, 6) equity, 7) economic implications, 8) methods issues, and 9) responses. There is a clear consensus amongst the papers in this review suggesting that changing climate patterns and weather extremes have substantial and wide-ranging effects on developing brains. A range of responses are proposed with an emphasis upon early intervention and better data.

Introduction

While healthy brain development and the factors that affect it have been studied for decades, the full implications of the topic have only recently gained broader academic and public attention [1]. This includes increased awareness of the profound personal and societal costs of negatively impacted brain development and the health disparities therein. For example, over 40% of children in low- and middle-income countries face the risk of not meeting their developmental potential due to extreme poverty [2] alongside a lack of access to education and other key resources. This leads to markedly lower annual earnings and longer-term health and social impacts in adulthood amongst a range of other considerations.

The increasing attention to the topic is reflected in the recent release of the World Health Organization position paper on optimizing brain health across the life course [3]. This paper notes several key determinants of brain health, including physical health, safety and security, learning and social connection, access to quality services, and healthy environments. Climate change has the potential to impact and interact with many of these determinants. Indeed, the authors conclude that “climate change contributing to ambient air pollution and increased risk of wildfires threaten the brain health of individuals and society as a whole.” [3, p. xvi]. These brain health implications are situated within a large and rapidly increasing body of evidence that addresses the physical and mental health impacts and implications of extreme and worsening environments [4,5]. These health impacts occur through complex systems ranging from direct (e.g., injury during an extreme weather event) to indirect

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effects (vector-borne diseases; health crises due to eroded healthcare infrastructure and social supports) that compound existing health disparities.

The implications of climate change for healthy brain development represent a prototypical example of these complex and cross-cutting relationships. This is a function of the nature of the brain itself. The brain is exceptionally sensitive to a wide range of threats across critical developmental periods as it is positively influenced by a plethora of biological, environmental, and social factors. As noted earlier, the costs to individuals and societies of negatively impacted brain development are profound – be it in the form of diagnosable developmental disability, reduced cognitive capacity, or areas of behavioral and emotional functioning more typically associated with the term mental-health [6]. Examples of the far-reaching implications of climate change for healthy brain development include impacts on developing fetuses, vector-borne illness, malnutrition, air pollution, and the degradation of and reduced access to key infrastructures such as education and healthcare systems.

Using scoping review methods, we have sought to develop a comprehensive, high-level description of the key risk domains that climate change presents with respect to healthy brain development, from the prenatal through to youth stages. While several papers describe literature in specific domains (e.g., air pollution and brain development), this review is amongst the first to address the totality of this topic. Capturing the breadth of these complex interrelationships, we argue, is important in the effort to bring a systematic lens to this problem and to inform efforts to target interventions and bridge knowledge gaps.

Methods

Scoping review methods were chosen for this review due both to the complexity and breadth of the topic and its attendant literature. Accordingly, we applied the Arksey and O'Malley [7] framework for scoping reviews, using the following 5 stages of: (1) identifying the question, (2) conducting the search, (3) selecting studies, (4) charting data, and (5) reporting results. Our review approach was also informed by Levac et al. [8]. The authors of the present review have expertise in health equity, poverty and climate change, neuropsychology, mental health, neuroepidemiology, climate epidemiology, and the health economics of climate change.

The question posed for this review was: what are the major considerations of the peer-reviewed literature that address climate change as it relates to brain development and health from early development through to youth populations? We defined the upper age limit of this range as 24 [9]. A key implication of this question is the requirement that the papers reviewed explicitly address climate change in the manuscript. This requirement affords the opportunity to examine how the literature is connecting climate change to brain development. As well, with the many domains involved and their complex relationships (e.g., heat extremes, air pollution, vector-borne disease, etc.), including papers that more broadly address climate variability, seasonality, and/or extreme weather events would make the review unfeasible. The unique contribution of the review is its breadth in capturing the many known systems involved in the brain development-climate nexus and identifying data gaps and promising intervention targets. The potential limitations of requiring the overt referencing of climate change in the selected papers were offset through the identification and summarizing of recent systematic reviews in each major theme. These summaries assist in contextualizing and describing the complete knowledgebase in each area. We present these summaries of reviews alongside the papers of focus.

An *a priori* search strategy was developed to identify the peer-reviewed literature relevant to this question. The review is registered with OSF Registries (10.17605/OSF.IO/3CF9E). The search, conducted in April 2022, covered the period from inception up to that point. The search was restricted to English language, peer-reviewed journals. The databases searched were PsycINFO, Pubmed, Scopus, and Google Scholar. These databases were chosen with Pubmed and PsycINFO being primary from a topic perspective with Scopus and Google Scholar adding breadth from broader literature. The search terms were ("climate" OR "climate change" OR "global warming" OR "weather" OR "heat") and ("child*" OR "youth" OR "adolescen*" OR "infant" OR "*natal" OR "utero") and ("psychiatr*" OR "neur*" OR "brain" OR "cognit*"). For Google Scholar, the search proceeded until 100 unsuccessful hits occurred after the last successful hit in the identified documents. A combined title and abstract review was conducted by one author (SK), with papers excluded if they did not address the combined topics of climate change, the relevant developmental periods, and brain development. Duplicates were removed. We included both papers that described research on original data, along with reviews and commentaries given the objective of synthesizing the breadth of these associations, and the value of expert commentaries to this end. Protocols were excluded. A full-text review was then completed by SK, SH, AM, and JG to validate choices about the final group of papers selected. In the few instances where a full text review left reviewers with different opinions about inclusion, a discussion was had about the discrepancies as a group and a decision arrived at by consensus. In no instance was consensus not achieved.

We charted the major themes [7,10] from the selected papers, grouping information as a function of (i) descriptors (e.g., year, country of publication, publication type, methods), (ii) the findings of studies that examined data and, (iii) a thematic synthesis [11] of all of the papers. All authors collaborated on interpreting the thematic analysis, going back to the original texts in the writing process. Findings were then summarized for this paper using a consensus process as was the determination of pertinent research, policy, and practice implications.

Results

The search results and article selection process are presented in Fig. 1 and Table 1. Although the thematic synthesis produced several key themes, it should be noted that many of the identified papers refer directly or indirectly to multifactorial or interacting risks, which cannot be placed into one category as multiple factors are implicated in producing negative developmental outcomes. For example, access to school is consistently mentioned as a key impact of events such as floods, with cognitive development, academic achievement, and related outcomes later in life cited as impacts. This access disruption occurs at the time of weather extremes, with grade advancement reduced and substantial numbers of children and youth not returning to school after the disruption [12,13]. Further, combined risks experienced by mothers during climatic disasters also interfere with prenatal development. A specific example related to climate refugees found that mothers in this situation in Bangladesh were three times as likely to have children with neurodevelopmental impairment [14].

Based on the thematic analysis, results are organized into the following nine themes: 1) heat extremes, 2) weather extremes and stress, 3) air pollution, 4) vector and waterborne illnesses, 5) malnutrition, 6) equity, 7) economic implications, 8) methods issues, and 9) responses. A broad overview of the processes described in this review can be found in Fig. 2. Where applicable, the data generated in this review were complemented by broader review of literature specific to the topic but not explicitly referring to climate change.

Heat extremes

Temperature extremes associated with climate change comprised a large part of the content of this review. The major emphasis was upon extreme heat exposure during pregnancy since environmental risks *in utero* can have wide-ranging and long-lasting impacts on

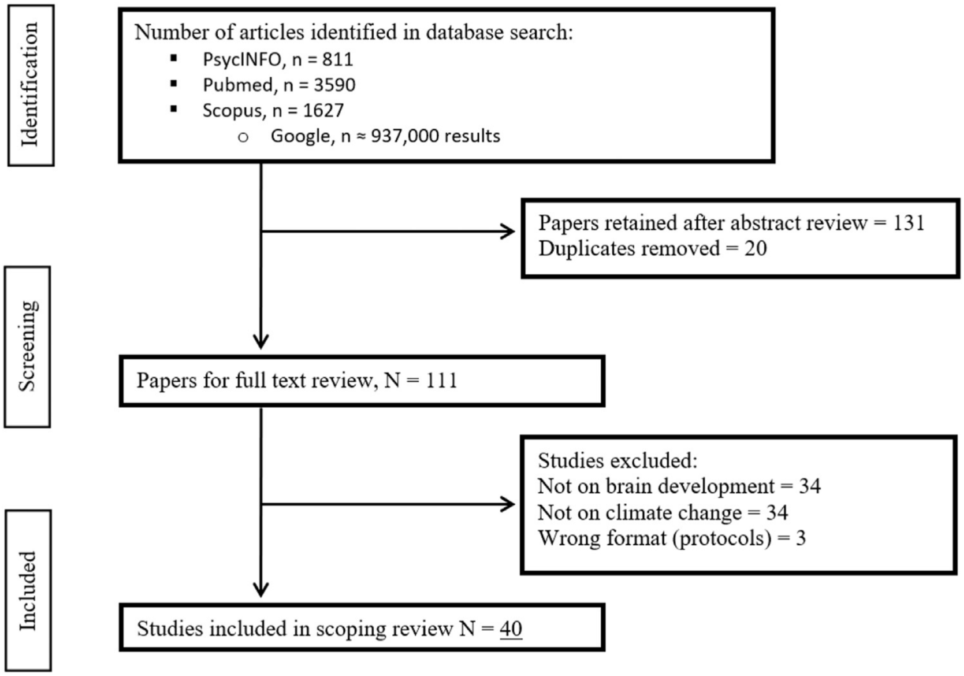

Fig. 1. Article selection flow diagram.

childhood development. The physiology of pregnancy involves increased cardiac output and decreased peripheral vascular resistance which makes hyperthermia more frequent and severe for pregnant women. Fetal circulation is also implicated, as maternal blood flow transfers to the skin for cooling [15,16]. The evidence-base for associations between heat exposure and increased risk of preterm birth, low birthweight, and stillbirth is well established, with heat stress the week before birth being the most critical window of exposure, although exposure during every trimester has been implicated in various studies [17]. Heat has also been linked to rarer maternal, fetal, and neonatal outcomes such as birth defects. While the nature and strength and types of associations vary across studies, prenatal heat exposure has also been linked to neural tube defects [15,18-20]. These impacts are magnified as a result of heat-related shorter gestational periods which, in turn, can lead to poorer neurocognitive outcomes and an increased risk of neuropsychiatric disorders [16,21-23]. Temperature anomalies at the prenatal stage have also been associated with lower academic achievement levels [24]. These observations from papers citing climate change align with the broader reviews that examine the impact of heat on fetal development [17,25]. Preterm birth has the most established association with maternal heat exposure, with the impacts on neural tube development being the most severe during the first 8 weeks of pregnancy.

Postnatally, heat exposure has been linked with poor sleep, poor cognition, and lowered school achievement [23]. On the acute end of the exposure risk spectrum, heatstroke in children, when not fatal, has been associated with severe, residual neurological deficits [26]. Further, a study among college students residing in dorms during heat waves found that those without air-conditioning had lower test scores and reaction times when compared with students in air-conditioned housing [27]. These observations are reflective of the broader literature on heat and postnatal development [28]. Heat extremes, as with other climate change-related pressures, also have indirect effects on developing brains through factors such as malnutrition.

Weather extremes and stress

Weather extreme-induced stress and brain injury were described as impacting brain development prenatally and throughout the developmental period postnatally [29–32]. For fetal development, stress experienced by pregnant women as a result of exposure to extreme weather events had significant implications. These impacts on fetal development interact with other brain health risks that attend poor food security and reduced access to healthcare and other resources due to damaged infrastructure [33]. Environmental stressors were also linked to epigenetic changes and a disrupted hypothalamic-pituitary-adrenal (HPA) axis which have an array of downstream health consequences [23,34]. Additionally, children are less able to withstand and are more impacted by elevated stress levels due to immature neurobiology, further exacerbating developmental impacts [31]. These impacts can result both from acute events, such as extreme storms, and stress resulting from chronic stressors that attend environmental degradation, which can have a range of impacts (e.g., parenting quality declining due to chronic stress; [23]). Further, epilepsy was described as having relevance to the topic of brain development. Specifically, weather extreme-caused stress, fatigue, and sleep deprivation, exacerbated by mood disorders and post-traumatic stress symptoms, can trigger and exacerbate seizures, deteriorate seizure control, and lead to neurological and cerebrovascular impacts [35]. All of these brain development implications of climate change are moderated by factors ranging from genetic variation, infrastructure resilience, housing quality, and impacts on global supply chains [35].

In the broader literature, there is extensive evidence that exposure to prolonged adversity leads to “toxic stress” in children, that is, continuous activation of the brain’s stress management system without relief, which can have long-lasting consequences into adulthood [36]. Toxic stress results from exposure to conflicts and disasters, as well as their prolonged aftermath including forced migration or being trapped in hazardous situations [37].

Air pollution

Climate change was described as being both worsened by air pollution and as compounding the problem of human exposure to air pollution which, in turn, has implications for brain health and development. The impacts of air pollution on brain health and brain development have been described both pre and postnatally [38].

Table 1
Article summary.

Paper	Country/Region	Article type and # of subjects	Major Findings
Aguilar A, Vicarelli M. El Niño and children: Medium-term effects of early-life weather shocks on cognitive and health outcomes. World Dev. 2022;150:105690. https://doi.org/10.1016/j.worlddev.2021.105690.	Mexico	Longitudinal study; 3339–4111 subjects	- Early-life (up to 2 years) weather shocks affect physical, cognitive, and behavioral development for children between 2 and 6 years. - Data collected in poor rural areas where families depend on agriculture - Government aid needed: financial support, food programs, employment opportunities
Anderko L, Chalupka S, Du M, Hauptman M. Climate changes reproductive and children's health: A review of risks, exposures, and impacts. Pediatr Res. 2020;87:414–9. https://doi.org/10.1038/s41390-019-0654-7.		Non-systematic review	- Air pollution and vector-borne diseases increase as temperature goes up, have negative impacts on brain development. - Climatic disasters impact mental health and emotion regulation. - Mental health services should be part of disaster response plans.
Auger N, Fraser WD, Arbour L, Bilodeau-Bertrand M, Kosatsky T. Elevated ambient temperatures and risk of neural tube defects. Occup Environ Med. 2017;74:315–20. https://doi.org/10.1136/oemed-2016-103956.	Canada	Retrospective cohort study; 887 710 fetuses (3–4 weeks post-conception)	- Elevated temperature related to neural tube defects (weak association).
Bartlett S. The implications of climate change for children in lower-income countries. Child Youth Environ. 2008;18:71–98.	U.S.	Comment	- Maternal stress/anxiety from exposure to climatic events when pregnant associated with lower cognitive and learning abilities in toddlers. - Diseases (e.g., malaria) associated with cognitive and neurological impairments. - Poverty exacerbates exposure to climatic events. Response needs to account for this. - Children can benefit from age-appropriate education and involvement.
Brumberg HL, Karr CJ. Ambient air pollution: Health hazards to children. Pediatrics. 2021;147:e2021051484. https://doi.org/10.1542/peds.2021-051484.		Non-systematic review	- Impacts of air pollution on development of central nervous system is of concern. - School-based exposure to air pollution can hinder academic success and lead to impaired neurobehavioral development. - Need policies to reduce exposure to air pollution.
Burke SE, Sanson AV, Van Hoorn J. The psychological effects of climate change on children. Curr Psychiatry Rep. 2018;20:1–8. https://doi.org/10.1007/s11920-018-0896-9.		Non-systematic review	- Increasing climate-related stressors (e.g., diseases, malnourishment) cause developmental delays. - Prenatal exposure also has negative mental health impacts.
Buthmann J, Ham J, Davey K, Finik J, Dana K., Pehme P, et al. Infant temperament: Repercussions of Superstorm Sandy-related maternal stress. Child Psychiatry Hum Dev. 2019;50:150–62. https://doi.org/10.1007/s10578-018-0828-2.	U.S.	Prospective cohort study; 380 mother-child dyads	- Offspring negative affect as a result of financial loss, lack of access to phone/electricity after the storm. - Exposure to storm early in the postnatal period leads to emotion dysregulation.
Cianconi P, Betrò S, Janiri L. The impact of climate change on mental health: A systematic descriptive review. Front Psychiatry. 2020;11:74. https://doi.org/10.3389/fpsyt.2020.00074.		Systematic Review	- Air pollution can induce neural instability. - Increased greenery improves children's cognitive development.
Dadvand P. Congenital anomalies: An under-evaluated risk of climate change. Occup Environ Med. 2017;74:313–4. https://doi.org/10.1136/oemed-2016-104193.	Spain	Comment	- Pregnant women are particularly vulnerable to heat stress. - Extreme heat has been associated with neural tube defects.
Donaldson SG, Van Oostdam J, Tikhonov C, Feeley M, Armstrong B, Ayotte P, et al. Environmental contaminants and human health in the Canadian Arctic. Sci Total Environ. 2010;408:5165–234. https://doi.org/10.1016/j.scitotenv.2010.04.059.		Non-systematic review	- Climate change can have negative effects on food harvest, which may pose serious repercussions for nutrient intake of Inuit children.
Evans GW. Projected behavioral impacts of global climate change. Annu Rev Psychol. 2019;70:449–74. https://doi.org/10.1146/annurev-psych-010418-103023.		Non-systematic review	- Flooding and severe storms that lead to displacement result in drops in academic achievements. - Drought is related to stunting, which delays school start and progress through early grades. - Drought related to reduced educational attainment for women, but not for men.
Gibbons ED. Climate change, children's rights, and the pursuit of intergenerational climate justice. Health Hum Rights. 2014;16:19–31.	U.S.	Comment	- Exposure to climatic events is of concern for physiological and mental development of children. It is exacerbated by malnutrition. - Climatic impacts disproportionately affect children, particularly those living in poverty.
Giudice LC. Environmental impact on reproductive health and risk mitigating strategies. Curr Opin Obstet Gynecol. 2021;33: 343–9.		Non-systematic review	- Populations of lower socioeconomic background are disproportionately exposed to environmental chemicals air pollution. - Exposure leads to negative health outcomes, specifically influencing reproductive and fetal/neonatal neurodevelopment.
Gulcebi MI, Bartolini E, Lee O, Lisgaras CP, Onat F, Mifsud J, et al. Climate change and epilepsy: Insights from clinical and basic science studies. Epilepsy Behav. 2021;116:107,791. https://doi.org/10.1016/j.yebeh.2021.107791.		Non-systematic review	- People with epilepsy are at increased risk from exposure to extreme climatic events and to vector-borne infections, both of which may increase seizures.
		Systematic review	

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Table 1 (*Continued*)

Paper	Country/Region	Article type and # of subjects	Major Findings
Haghighi MM, Wright CY, Ayer J, Urban MF, Pham MD, Boeckmann M, et al. Impacts of high environmental temperatures on congenital anomalies: A systematic review. Int J Environ Res Public Health. 2021;18:4910. https://doi.org/10.3390/ijerph18094910.			- Some association between heat exposure and neural tube defects. - Pregnant women are a high-risk group for heat exposure. socioeconomic status an important factor as mitigates access to resources, such as air conditioning.
Khan NZ, Muslima H, Shilpi AB, Majumder SK, Khan AE. Neurodevelopmental outcomes in children born to climate refugee mothers in Bangladesh: Experiences from cyclone Aila. Mymensingh Med J. 2016;25:746–50.	Bangladesh	Cross-sectional study; 819 mother-child dyads	- Neurodevelopmental impairments three times higher among children born to CR mothers. - For refugees, pregnant women require antenatal care.
Laurent JGC, Williams A, Oulhote Y, Zanobetti A, Allen JG, Spengler JD. Reduced cognitive function during a heat wave among residents of non-air-conditioned buildings: An observational study of young adults in the summer of 2016. PLoS Med. 2018;15: e1002605. https://doi.org/10.1371/journal.pmed.1002605.	U.S.	Observational study; 44 subjects	- Heatwaves impact reaction time and reduce throughput for non-AC residents compared to AC residents.
Malaspina D, Howell EA, Spicer J. Intergenerational echoes of climate change. JAMA Psychiatry. 2020;77:778–80. https://doi.org/10.1001/jamapsychiatry.2020.0604.	U.S.	Comment	- Pregnant women experience hyperthermia more frequently and more severely during the heatwaves. - Adverse outcomes include preterm birth and increased risk of still birth. Preterm birth a risk factor for a range of psychiatric disorders.
Mathiarasan S, Hüls A. Impact of environmental injustice on children's health – Interaction between air pollution and socioeconomic status. Int J Environ Res Public Health 2021;18:795. https://doi.org/10.3390/ijerph18020795.		Non-systematic review	- Young children more susceptible to air pollution, which can induce neurotoxicity, altering the brain and causing negative health outcomes - Lower socioeconomic status increases the likelihood of exposure.
Miles-Novelo A, Anderson CA. Climate change and psychology: Effects of rapid global warming on violence and aggression. Curr Clim Change Rep. 2019;5:36–46. https://doi.org/10.1007/s40641-019-00121-2.		Non-systematic review	- Malnourishment at the age of 3 is associated with hyperactivity and aggression at age 8.
Nomura Y, Davey K, Pehme PM, Finik J, Glover V, Zhang W., et al. Influence of in utero exposure to maternal depression and natural disaster–related stress on infant temperament at 6 months: The children of Superstorm Sandy. Infant Ment Health J. 2019;40:204–16. https://doi.org/10.1002/imhj.21766.	U.S.	Longitudinal study; 408 mother-child dyads	- Exposure to the storm increased maternal depression, related to lower emotion regulation. - Physiological response to stress has negative impact on fetus, linked to stress reactivity and psychopathology.
O'Donnell S. The neurobiology of climate change. Sci Nat. 2018;105:1–7. https://doi.org/10.1007/s00114-017-1538-5.	U.S.	Comment	- Climate change and its effects, experienced directly or through information on climatic impacts, can induce trauma-responsive cognitive states.
Olson DM, Metz GA. Climate change is a major stressor causing poor pregnancy outcomes and child development. F1000 Res. 2020;9:1222. https://doi.org/10.12688/f1000research.27157.1.		Non-systematic review	- Climate change leads to adverse pregnancy outcomes and impaired developmental trajectories.
Pacheco SE. Catastrophic effects of climate change on children's health start before birth. J Clin Invest. 2020;130:562–4. https://doi.org/10.1172/JCI135005.	U.S.	Comment	- Maternal exposure to climatic events during pregnancy is associated with a range of health issues, including preterm birth, LBW, neurodevelopmental disorders, and metabolic derangements. - Exposure of children to air pollution has been linked to systemic and neurological inflammation and cognitive dysfunction, among other issues.
Payne-Sturges DC, Marty MA, Perera F, Miller MD, Swanson M, Ellickson K, et al. Healthy air, healthy brains: Advancing air pollution policy to protect children's health. Am J Public Health. 2019;109:550–4. https://doi.org/10.2105/AJPH.2018.304902.	U.S.	Comment	- Fossil fuel burning associated with increased air pollution, which has negative impacts for neurodevelopment. - Some issues related to exposure to air pollution include preterm birth, LBW, developmental delay, and symptoms of anxiety, depression.
Perera FP. Multiple threats to child health from fossil fuel combustion: Impacts of air pollution and climate change. Environ Health Perspect. 2017;125:141–8. https://doi.org/10.1289/EHP299.	U.S.	Comment	- The adverse physical and mental health outcomes of exposure to climatic events and air pollution have economic implications, lowering lifetime earnings. - Black women exposed to air pollution experience increased odds for morbidity outcomes. - Low socioeconomic status is associated with poorer outcomes, amplified by malnutrition and lack of access to supports.
Perera F, Ashrafi A, Kinney P, Mills D. Towards a fuller assessment of benefits to children's health of reducing air pollution and mitigating climate change due to fossil fuel combustion. Environ Res. 2019;172:55–72. https://doi.org/10.1016/j.envres.2018.12.016.		Systematic review	- Air pollution is linked to adverse outcomes for child cognitive, neurobehavioral, motor, and mental development. - Some indication that exposure to air pollution after birth has a stronger association with negative outcomes.
Ruszkiewicz JA, Tinkov AA, Skalny AV, Siokas V, Dardiotis E, Tsatsakis A, et al. Brain diseases in changing climate. Environ Res. 2019;177:108,637. https://doi.org/10.1016/j.envres.2019.108637.		Non-systematic Review	- Climatic changes, especially droughts, pose a significant risk for vulnerable populations in developing countries. - Changing climate has serious implications for diseases spread by mosquitos and ticks (such as malaria and Lyme disease). - Growth of harmful algal blooms leads to accumulatio of neurotoxins in seafood, which increases the risks of poisonings that may influence the brain and other organs.

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Table 1 (*Continued*)

Paper	Country/Region	Article type and # of subjects	Major Findings
Sahni GS. The recurring epidemic of heat stroke in children in Muzaffarpur, Bihar, India. Ann Trop Med Public Health. 2013;6:89–95. https://doi.org/10.4103/1755-6783.115203.	India	Retrospective study; 50 subjects	- Heat shocks associated with child morbidity and mortality. Adverse outcomes are seen for children from overcrowded housing and with poor access to electricity, hygiene, and ventilation.
Schiff SJ, Ranjeva SL, Sauer TD, Warf BC. Rainfall drives hydrocephalus in East Africa: Clinical article. J Neurosurg Pediatr. 2012;10:161–7. https://doi.org/10.3171/2012.5.PEDS11557.	East Africa	Longitudinal study; 696 subjects	- Infections tend to occur when the rainfall is intermediate.
Stanley F, Farrant B. Climate change and children's health: A commentary. Children. 2015;2:412–23. https://doi.org/10.3390/children2040412.	Australia	Comment	- Extreme weather events lead to stress and trauma, which may negatively affect brain development, as well as produce long-term cognitive and mental issues.
Syed S, O'Sullivan TL, Phillips KP. Extreme heat and pregnancy outcomes: A scoping review of the epidemiological evidence. Int J Environ Res Public Health. 2022;19:2412. https://doi.org/10.3390/ijerph19042412.		Scoping review	- Extreme heat related to neural tube defects. - Gap in epidemiological literature from the global south.
Tang H, Di Q. The effect of prenatal exposure to climate anomaly on adulthood cognitive function and job reputation. Int J Environ Res Public Health. 2022;19:2523. https://doi.org/10.3390/ijerph19052523.	China	Longitudinal study; 17,105 subjects	- Prenatal exposure to climatic events can lead to economic loss through decreased cognitive functioning and lower job reputation in adulthood. - More vulnerable groups include females and those form less-developed regions.
Thompson HE. Climate "psychopathology": The intersection of mental and physical health in the climate emergency. Eur Psychol. 2021;26:195–203. https://doi.org/10.1027/1016-9040/a000433.		Non-systematic review	- Climate-related stress has negative impacts on brain development. - Need further research on climate-related cognitive experiences, especially on the link between climate-induced stress and the physical and mental health.
van Nieuwenhuizen A, Hudson K, Chen X, Hwong AR. The effects of climate change on child and adolescent mental health: Clinical considerations. Curr Psychiatry Rep. 2021;23:1–9. https://doi.org/10.1007/s11920-021-01296-y.		Non-systematic review	- Extreme heat exposure carries multiple risks for pregnant women, including physical and mental health as well as earnings in adulthood for children. - Need further longitudinal research as well as community-based participatory research and qualitative studies.
van Zutphen AR, Lin S, Fletcher BA, Hwang SA. A population-based case–control study of extreme summer temperature and birth defects. Environ Health Perspect. 2012;120:1443–9. https://doi.org/10.1289/ehp.1104671.	U.S.	Case-control study; 6422 cases and 59,328 controls	- No statistically significant relationships between extreme heat and birth defects.
Vergunst F, Berry HL. Climate change and children's mental health: A developmental perspective. Clin Psychol Sci. 2022;10(4):767–85. https://doi.org/10.1177/21677026211040787.	Canada	Comment	- Exposure to extreme events induces stress in pregnant mothers, is related to dysregulation of HPA axis stress response system in children - Climatic events and the associated disruptions in daily life can delay attainment of developmental milestones and increase mental health vulnerability.
White B. States of emergency: Trauma and climate change. Ecopsychology. 2015;7:192–7. https://doi.org/10.1089/eco.2015.0024.	U.S.	Comment	- Climatic events may lead to trauma, which impairs cognitive functioning and ability to assess and respond to environmental changes.
Williams PC, Marais B, Isaacs D, Preisz A. Ethical considerations regarding the effects of climate change and planetary health on children. J Paediatr Child Health. 2021;57:1775–80. https://doi.org/10.1111/jpc.15704.	Australia	Comment	- Climatic events pose a risk to children, endangering them with potential harm, susceptibility to infectious diseases, and the psychological distress resulting from surviving such events. - Undernutrition leads to mortality risks and may cause structural brain changes.
Yamashita N, Trinh TA. Effects of prenatal exposure to abnormal rainfall on cognitive development in Vietnam. Popul Environ. 2022;43:346–66. https://doi.org/10.1007/s11111-021-00394-6.	Vietnam	Longitudinal study; 1250–1800 subjects	- Positive rainfall shocks have positive impact on cognitive development. However, positive effects are absent by age 10 and 15.

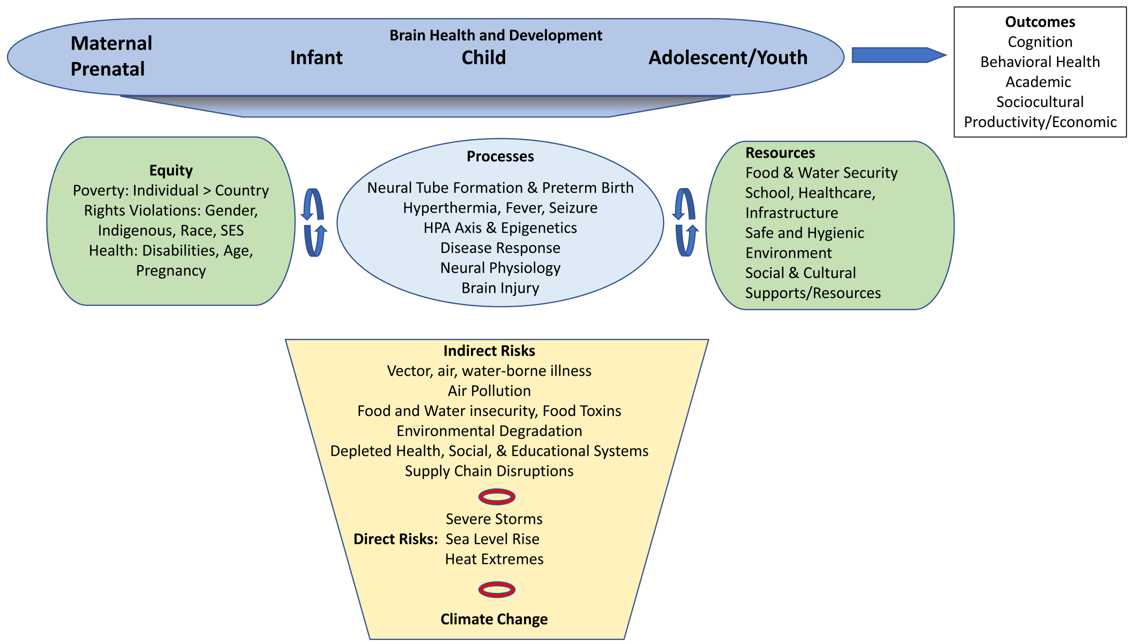

Fig. 2. Impact pathways between heat stress and neonatal health.

Polycyclic aromatic hydrocarbon (PAH) exposure prenatally and postnatally has been associated with lowered general IQ, structural neural alterations evidenced in MRI studies, and epigenetic, transgenerational alterations [39]. Associations between air pollution with attention deficit-hyperactivity disorder (ADHD) and autism spectrum disorder (ASD) are also addressed across many regions globally [21,39]. Other pollutants implicated across a range of brain and behavioral impairment risk domains, though with some inconsistent findings, include PM2.5 and NO2 with an emphasis on traffic-related air pollution [29,39,40]. Postnatal exposure risks have highlighted the school context, documenting implications for academic achievement and neurodevelopment [38,41,42]. Specifically, there is evidence of lower academic performance for children exposed to outdoor air pollution, linked to slower cognitive development and inhibited working memory [38].

Broader reviews not specifying climate change support the observations of the papers captured in the current review, describing both neurodevelopmental and neurodegenerative risks. PM2.5 and ultra-fine particulate matter (UFPM) are described as being of particular risk given their ability to enter the circulation system and the brain as well as gaining direct access through the nasal olfactory mucosa [43]. Both prenatal and postnatal exposures present risks across an array of cognitive developmental domains alongside ASD and ADHD, though ADHD findings are more mixed [44,45]. Reviews also described associations between traffic-related air pollution (TRAP) exposure and poorer school performance [46]. Several MRI studies have examined the association between air pollution and child brain structure. Associations include, for exposed children, less white matter surface area and microstructure, smaller volumes and/or less density within the caudate nucleus, altered resting-state functional connectivity and brain activity to sensory stimuli, and patterns of cortical thinness [47]. Animal models on the neurodevelopmental impacts of air pollution describe the disruption of reelin homeostasis, excitatory/inhibitory imbalance, and changes in the gut microbiota [43]. Other impacted processes that have been flagged include the e4 allele of the apolipoprotein E gene, glutathione-S-transferase gene polymorphism and neuroinflammation [45].

Vector and waterborne illnesses

While having less literature than other areas, vector and waterborne illnesses related to climate change were described as having brain health and development impacts in several papers. Malaria and dengue fever prevalence were associated with weather extremes and were described as leading to increased prenatal risks of anomalies and premature birth with associated brain development impacts [21]. Congenital Zika virus is associated with microcephaly and other birth defects and its increased prevalence has also been associated with climate change [29,48].

Postnatal impacts due to vector- and water-borne illnesses were also described. Specifically, children with malaria are more likely to exhibit neurological conditions such as epilepsy, cognitive impairment, and behavioral impairments including attention deficit disorder, hyperactivity and aggressive behavior [48]. For children with pre-existing epilepsy, vector-borne infections can trigger or exacerbate seizures [35]. In addition to mosquito-borne illnesses, the climate change implications for an increased risk of tick exposure were described in the reviewed literature. Tick bites can lead to Lyme disease which can cause neuropsychiatric symptoms such as altered affect, behavior, cognition and perception as well as tick-borne encephalitis [29,48].

Waterborne illnesses were also addressed in this context. Exposure to parasites such as cryptosporidium and diarrhea have been associated with worsened language development and academic performance, with examples provided from storm and rain event extremes in Nicaragua and Brazil [33]. Climate change also has implications for the increasing prevalence of harmful algae blooms: these blooms (e.g., blue-green cyanobacteria and dinoflagellates) produce neurotoxins (e.g., microcystin, saxitoxin, brevetoxin) that accumulate in fish and seafood and, in turn, increase the risk of human poisoning that affects brain health and development [48].

Outside of papers identified in this review that specifically denote climate change in connections between disease and brain development, the broader literature also supports the observations described above. Pathogen exposure through contaminated water sources causes enteric disease and dehydration, which have been linked to neurodevelopment issues and poorer cognition in adulthood due to childhood exposures and impacts on the gut-liver-brain axis [49]. Malaria, especially when severe or after multiple episodes, has been found to have major neurodevelopmental implications with persisting cognitive impacts that are compounded through anemia and kidney damage [50]. Similar reviews of the neurodevelopmental impacts of other arthropod-borne viruses such as dengue fever, Zika [51] and tick-borne encephalitis and Lyme disease [52], validate the observations made in papers captured in the current review and suggest additional diseases to be considered (e.g., West Nile Virus; [51]).

Malnutrition

The implications of climate change-induced malnutrition and subsequent brain development was a subject of considerable commentary. Malnutrition, in this context, was generally attributed to drought and extreme hydrological events [13]. Authors described the evidence base associating malnutrition early in life with structural brain changes [48,53-55]. Further risks commented on included observations that malnourished children are more vulnerable to neurodevelopmental toxins (e.g., lead). Malnourished children also lack energy, making them less able to explore their environments and experience the cognitive stimulation levels that are important to development [33]. Maternal malnutrition may also lead to low birth weight and other adverse birth outcomes that impact childhood development. Drought-impacted contexts are also ones where the consumption of drought-resilient foods increases. Plants such as cassava seeds and grass pea contain neurotoxins which are associated with neurological disease [48]. Rainfall shocks were highlighted specifically amongst the papers reviewed in relation to their diverse impacts on nutrition and developmental outcomes. Positive rainfall shocks in Vietnam, which were related to improved income and nutrition, particularly in the early stages of gestation, were associated with better cognitive development, though this association was absent after the age of 10 [56]. Contrastingly, in Mexico, extreme rainfall exposure from gestation through to 2 years of age was associated with poorer cognitive development between the ages of 2 and 6, as rainfall shocks here lead to flooding, which resulted in reduced income and lower quality nutrition [57]. These data were from rural and poor areas with a greater reliance on agriculture.

The broader literature validates the many cascading effects of climate change on food security globally [58,59]. As well as reduced crop yield, increased levels of carbon dioxide can reduce the protein and micronutrient content of crops such as rice, wheat, barley, and potatoes [58]. Malnutrition has been consistently related with poor cognitive neurodevelopment and, more broadly, mental health, though with some indication of negative impacts being reversible if nutrition is improved before age 8 [60]. Similarly, malnutrition is consistently associated with poorer academic outcomes (e.g., meta-analysis odds ratio of 0.48) amongst school children [61].

Equity

Issues related to equity were mentioned and discussed in several papers, with some drawing particular attention to environmental injustices [20,38]. Specific areas of concern were socioeconomic status, gender, and race. Considering poverty at a country level, from prenatal to postnatal exposures, residing in under-served geographical regions and countries was described as a risk for greater heat exposure and subsequent impacts on brain development and academic achievement, owing to aspects such as school education, parental education, and nutrition [24,56]. Disadvantaged children face greater adverse exposures related to air pollution and brain health [13,38,41,42]. Further, people from disadvantaged settings are also less likely to have the resources to be prepared for extreme weather events. For instance, there are profound disparities in access to adaptation strategies (e.g., air-conditioning) when exposed to heat. Framed as ‘thermal inequities’, people in resource-poor settings lack access to air-conditioning [19], and experience greater risks for child health crises such as heatstroke, which can lead to brain damage [26]. Conversely, persons with access to more social capital often demonstrate greater resilience towards extreme weather events [13].

Females, globally, were described as being at greater risk, even aside from the maternal health considerations covered previously. Drought has been observed to affect girls’ and women’s educational attainment more in rural areas of Indonesia, thought to occur as a function of boys being better safeguarded, given the prejudice against the female offspring; as such, girls and women experience greater malnutrition, and increased labor demands and income losses during the early childhood period [13]. Indeed, girls from economically deprived countries are particularly susceptible to worse cognitive performance due to malnutrition [13]. Racialized identity has been implicated as well, with Black women, in association with air pollution exposure, evidencing greater small birth weight risks, which are linked to neurodevelopmental issues [62]. Further, Indigenous status emerged in relation to the changes that climate change is causing with respect to access to ‘country food’ – hunted animals taken from the land, which impacts dietary health and, in turn, cognition [63]. Authors commented that despite these prominent equity implications, very little data are available from the Global South and resource-poor settings with which to capture impacts and direct responses [20].

Considering the broader literature across climate-brain health and neuro-development domains, the topic of inequitable impacts has been extensively commented upon. The implications of poverty and inequities are cross-cutting. Equity has been highlighted in the recent WHO position paper on optimizing brain health across the life course [3]. The impacts of missed potentials in children for brain development can lead to and further perpetuate cycles of poverty, social and health inequities [3,64]. Specific observations in the papers reviewed, such as those related to fine particle exposure and inequitable impacts, are also reflected in the broader literature [65].

Economic implications

A substantial amount of commentary was directed towards the economic implications of the brain development impacts of climate change. Brain development challenges lead to lower school attainment and reduced employment/productivity outcomes. Several broad estimates were captured in this review. The estimated direct costs of unmitigated climate change in Asia and Africa are estimated at 7–10% of the annual GDP [55]. Climate change also directly contributes to undernutrition, which negatively impacts cognitive development, further increasing the economic costs. Payne-Sturges et al. [40] noted an estimated U.S. annual cost (resulting from medical care, lost economic productivity etc.) of environmentally mediated childhood neurodevelopmental disorders of $74.3 billion, with a substantial component of these impacts understood to be climate change-related. More specific estimates and evidence include the observation that a reduced IQ at 5 years of age, associated with PAH exposure, was predicted to significantly lower lifetime earnings [62]. The same prediction was made with respect to heat exposure [22]. For China, it was estimated that prenatal exposure to climate anomalies, measured through sea surface temperature anomalies of 1°, could lead to a 1.09-billion-dollar reduction in earnings per year in adulthood due to impaired cognitive function [24].

The human capital implications of climate change are complex. Varying as a function of the type of climate pressures and individual and population access to resources, an array of social, behavioral, emotional, and cognitive responses can impact productivity across the lifespan. As discussed in the present review, neurodevelopment and cognition as associated with climate change factors are important contributors to academic achievement. Academic achievement, in turn, is one of the most important contributors to human capital and is a key factor in considering the economic consequences of climate change [66]. Economic impact estimates such as those identified in this review must be considered preliminary, however, as the longer-term productivity effects of climate change via brain health impacts on the young are difficult to model [67]. This challenge is one both of the complex interactions and interference from various factors in the long-term effects, and a lack of sufficient, comparable and longitudinal data to support the solution of such a long-time horizon problem [68].

Methods issues

The primary methods challenge that was apparent from this review was the difficulty establishing causality with respect to the effects of climate on healthy brain development. This difficulty is further exacerbated by the complexities of attributing specific extreme weather events to climate changes. Generally, it was understood that acute weather events/disasters are much more amenable to establishing causation than gradually changing weather patterns [23]. Several authors commented on the need for more longitudinal data to strengthen conclusions regarding causality [22] and, generally, the need for more granular data on the neurocognitive impacts of weather patterns and events [32]. Authors called for both better epidemiological data alongside qualitative, community-engaged studies from which the nuanced influences of climate change on children and youths' cognitive and emotional health might be better understood [22].

There were several more specific challenges that were highlighted. It was evident across papers that assessing cognition, particularly at a population level, can be challenging, with academic achievement at times used as a proxy for neurocognitive development (e.g., [24]). This can be problematic, for although there is a relationship between academic achievement and cognitive capacity, there are other important influences in this relationship such as socioeconomic status. Differing approaches to assessments in several domains have similarly been highlighted, such as the type of ASD assessment tool used, pollutant type, and operationalizing variables such as heatwaves and exposure [20,39]. The heterogeneity of measurement, both of climate exposures and brain health outcomes, impact the generalization of findings across studies. Other complicating factors include lacking data at an appropriate geographical and temporal scale [13], the use of self-report exposure metrics [19], lack of data on exposure buffers such as housing quality [18], and data lost due to preterm deaths and death at the time of birth. These factors make data interpretation challenging and, alongside the complexity of the climate change-brain health connection itself, likely contribute to variable findings observed across studies in this area.

The challenges described above resonate with observations and commentary in the broader literature, including climate change and mental health research [69]. The lack of longitudinal data is frequently referenced as are recommendations for more quasi-experimental and experimental designs. The latter emerged in the present review in the form of animal model experiments related to fine particulate exposure. There are also emerging longitudinal cohort studies and designs (e.g., [70]) that could provide excellent sources of information on the impacts of climate change on brain health and development impacts with the inclusion of consistent and validated metrics that capture these variables. Detection and attribution (D&A) studies could also be implemented in the future to ensure more robust causal inference [71]. D&A studies have been used in other areas of climate change and health such as heat and childhood mortality in Africa, but no study was found focusing specifically on brain health.

Responses

Interventions through which the healthy brain development risks posed by climate change might be reduced were not the emphasis of most papers, though did receive some comment. One general emphasis was on the importance of high-income countries, i.e., those most responsible for climate change, providing support to LMICs that are bearing the brunt of the brain health impacts of climate change [53]. Regarding air pollution, it was recommended that policy be enhanced to control emissions and to address modifiable behaviors [41], with authors suggesting that even modest changes in air pollutants could lead to substantially reduced brain health risks for developing fetuses and children [62]. This suggestion bridges back to the economic argument about ameliorating the lost productivity risks that pollutants pose as a function of brain health. Within countries, cash transfers for populations most affected by climate pressures was suggested alongside food and temporary employment assistance – again framed as a strategy that can ameliorate a range of risks including those related to brain development [57].

Improved antenatal care for climate refugee mothers was suggested given their markedly increased risks [14]. As well, improved greenery in urban areas was suggested as an intervention. This work highlighted the connection between green spaces, exercise, and social connectedness which are known to improve the neurocognitive functioning of children and youth [72]. One small U.S. study suggested some potential benefits to enhanced access to air-conditioning for students, though the findings were inconclusive [73]. Lastly, one of the earliest papers captured in this review highlighted the benefits of engaging children themselves [33]. They noted the mental health benefits of having children informed, engaged, and involved in responding to disasters – providing them with a sense of control, hope, and competence, and inferring to spillover effects in developmental domains. These recommendations gleaned from the papers reviewed generally align with strategies put forward in the broader health frame [5].

Discussion

This scoping review was undertaken to describe the academic literature that implicates climate change in brain development and health from fetal through to youth age ranges. The papers in this area suggest that changing climate patterns and weather extremes have substantial and wide-ranging effects on developing brains. These relationships occur within complex systems with both direct (e.g., hyperthermia, brain injury) and indirect (e.g., vector borne illness, malnutrition) effects, indexing as a function of the weather variables involved and geographic contexts alongside population, socioeconomic, and cultural characteristics. It is a consistent observation that individuals and populations lacking resources and experiencing inequities, as in other climate-health impact relationships [5], have the poorest outcomes.

While keeping the review anchored to the term "climate change" limited the depth of the review in each topic area, this approach had two advantages. First, this strategy helps with understanding how researchers are positioning climate change in reference to these issues. Our review suggests that while this referencing is likely increasing, authors have yet to routinely tie in climate change with work examining weather-brain health impacts in this area. Second, establishing this constraint kept the review feasible in terms of the numbers of papers captured – allowing for a breadth of topics covered that would not have otherwise been possible given our resources. Generally, it was found that while some nuances were not captured as became evident in considering broader literatures, the papers reviewed covered the most pressing issues in each area. A similar trade-off with a similar rationale was undertaken in another recent review capturing the literature on climate change and mental health [4]. Other limitations include limited coverage of brain development implications for older adolescents and youth and the above-mentioned reliance on data that is largely associational with variable metrics. It can also be difficult distinguishing between brain development and the much broader frame of mental health, which attends to issues such as eco-anxiety [69]. Finally, while attending to brain development early in life is clearly a priority, it needs to be acknowledged that climate change has serious implications for brain health throughout the lifespan (e.g., air pollution, heat, and dementia[74]).

Conclusions

The authors of the papers reviewed were essentially unanimous in arguing that healthy brain development should be prioritized in climate mitigation and adaptation responses since it is fundamental to all aspects of human health and wellbeing. It might also be argued, as well, that healthy brain development is a key consideration in the development of resilient communities that will be essential in humans' responses to climate change. While descriptions of responses were less well-articulated than those of problems, several points of intervention were highlighted. Specific domains include attention to maternal health and wellbeing as a point of leveraged intervention [75] and the potential to mitigate the impacts if caught early enough [30].

Authors also highlighted the need to prioritize sustaining educational and healthcare infrastructure and addressing stress exposure during extreme weather events [12,13,23,29,33]. Moreover, addressing disparities in the design of mitigation and adaptation responses related to brain development has the potential to reduce the threat-multiplying impacts of climate change on disadvantaged populations. Brain development is a critical variable in systems of compounding inequities [76].

A key aspect in the design of responses will be both a better availability of data with which to target points of leverage in policy and systems design, and with which systems-level interventions might be assessed and improved. The generation of evidence-derived leverage points in addressing the complex systems attending issues such as those described in this review are likely to produce the best results (e.g., leverage analysis in adaptation and farming in Africa [77]). Such work, in the frame of brain health, will require some significant shifts away from practices which have historically emphasized linearity in effects as well as a focus on individual-level impacts in ways that do not map well either onto climate-health effects nor the generation of effective responses [78]. Furthermore, this review has not only highlighted the difficulty in establishing causality and effect size in a given risk area due to associational data, it has also highlighted the challenge of assessing the *relative* risk of one factor over another in a given context. The assessment of relative risk will be key to assessing points of leverage and targeting interventions as a function of the setting. This might factor in location and timing (e.g., heat and storms being risks at certain times of the year in certain places) and available resources (e.g., where upgrading homes to become more heat resilient is not considered feasible due to poverty, vaccines and medical responses for vector and water-borne illnesses might be prioritized).

Additionally, more basic research in neuroscience will be needed to fully describe the cellular and molecular mechanisms through which different climate exposures are impacting brain development. Issues of equity and disparities will also need to be emphasized, as research and response design continue to poorly represent those most impacted [13,38,62,79].

In conclusion, this review suggests that climate change is having serious and far-reaching implications for healthy human brain development. It is imperative that this topic has more prominence in work centering on the human health implications of climate change, given its essential role in the physical, mental, and social wellbeing of human populations.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Sean A. Kidd: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Writing – original draft, Writing – review & editing. **Jessica Gong:** Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Alessandro Massazza:** Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Mariya Bezgrebelna:** Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Yali Zhang:** Writing – original draft, Writing – review & editing. **Shakoor Hajat:** Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing.

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